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The effect of bias in gas temperature measurements on the control of a Solid Oxide Fuel Cells system

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HIGHLIGHTS

- This is a study on Fuel Cell control including bias on temperature measurements.
- The deviation between desired and effected control due to this bias is important.
- The effect is such, that one case failed.
- We show that with simple design improvements the problem may be mitigated.

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ABSTRACT

In this paper the effect of systematic errors in gas temperature measurements on the thermal control of a Solid Oxide Fuel Cell system is demonstrated. Three control schemes were tested under two different conditions. First, the real gas temperature at the point of interest was used as input for the controller. Second, the reading of the thermocouple that takes the measurement at the same point was used as input. The second approach included the bias on the measurement due to radiation and heat conduction on the thermocouple. The results showed an overestimation of temperatures with important influence on the system control. Furthermore, in one case the system could not follow the required power demand and it failed. A successful solution to the problem was obtained by increasing the dimension of the system's heat exchanger.

1. Introduction

An efficient control system is paramount for the operability and the good performance of fuel cell systems. It allows the regulation of power output, temperatures and economic performance under a dynamic working environment where they need to operate. Several methodologies have been broadly investigated, such as Proportional-Integral-Derivative controllers (PID), Model Predictive Control (MPC), Artificial Neural Networks and Real-time Optimisation [1–5]. Similarly, different control strategies such as strategies for rapid load following, prevention of fuel starvation, optimal efficiency [7–10], etc. have been studied. Whichever the employed method, a correct feedback from the fuel cell system – voltage, current, temperatures, pressures, flow rates etc. – is mandatory for the control system to perform adequately.

This may be a subtle point for the control of high or intermediate temperature fuel cell systems. In common practice gas temperature measurements in those systems are taken with thermocouples simply dipped into the gas streams of interest. However, it was shown in previous publication [11] that an important bias may occur in such measurements on Solid Oxide Fuel Cell (SOFC) systems due to the radiation effects between the thermocouple and the surrounding solids. The discrepancy between the real and the measured gas temperature depends mainly on factors such as the temperature difference between the gas and the enclosing solids, the gas velocity, transfer factors of radiative exchange etc.

Systematic errors of this nature may have serious effects on the thermal management and generally on the control of fuel cells. To demonstrate those effects this paper studies simple cases of PID control on an SOFC system. More specifically it presents and compares three different approaches for simple thermal control of the system under two conditions. First taking for granted that the measured gas temperature is the real one,

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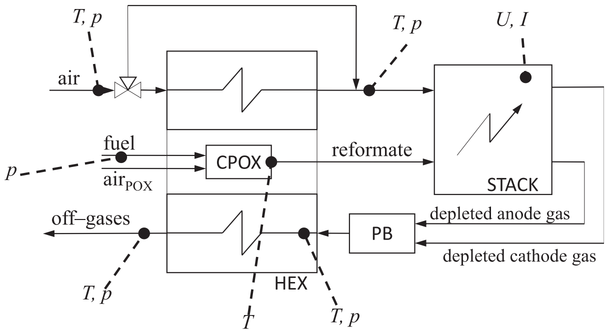

Fig. 1. Schematic flow diagram of the HoTbox™. Reproduced from Ref. [11] by permission from Whiley.

Table 1
Six control scenarios for SISO PID control. There are three options for the controller output and two options for the input.

		Controller input	
		Real gas temperature (exit cold stream HEX)	Thermocouple reading (exit cold stream HEX)
Controller output	Valve position	1A	1B
	Air ratio	2A	2B
	Fuel power	3A	3B

which, in fact, is the usual case in relevant publications. Second, simulating the behaviour of the thermocouple that makes the measurement and including the radiation bias in the control scheme. This analysis shows that depending on the control feedback, the effect of the difference between measured and real gas temperatures may vary from small to important that may even lead to failure of the system.

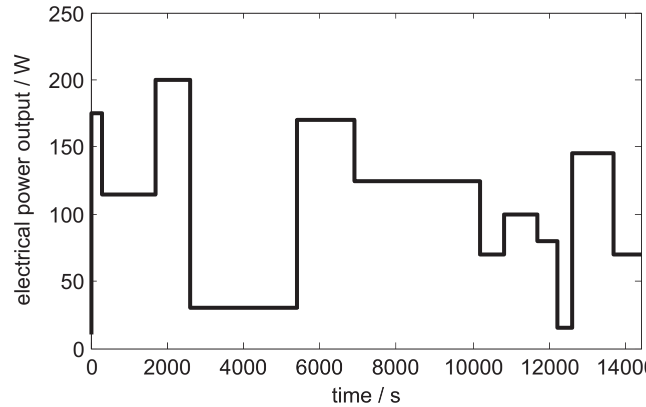

Fig. 2. Power scenario upon which different control schemes were tried.

The paper comprises five sections. The second section that follows gives an overview of the studied SOFC system. Section three presents the six control schemes tested by simulation on the system as well as the exact configuration of the PID controller. All results are deployed in the fourth section and the effects of different approaches are discussed. For one case that failed due to the systematic error in temperature measurement a solution is given with structural changes on the system. Finally, the article concludes in Section 5.

2. The studied SOFC system, its model and validation

The employed system model is an altered version of a model simulating the HoTbox™, a product of HTceramix–SOFCpower [12,13] and a prototype of an SOFC-based generator designed for co-generation. The model is built in gPROMS® [14] and a layout of the system is given in Fig. 1. It comprises a 500 W SOFC stack

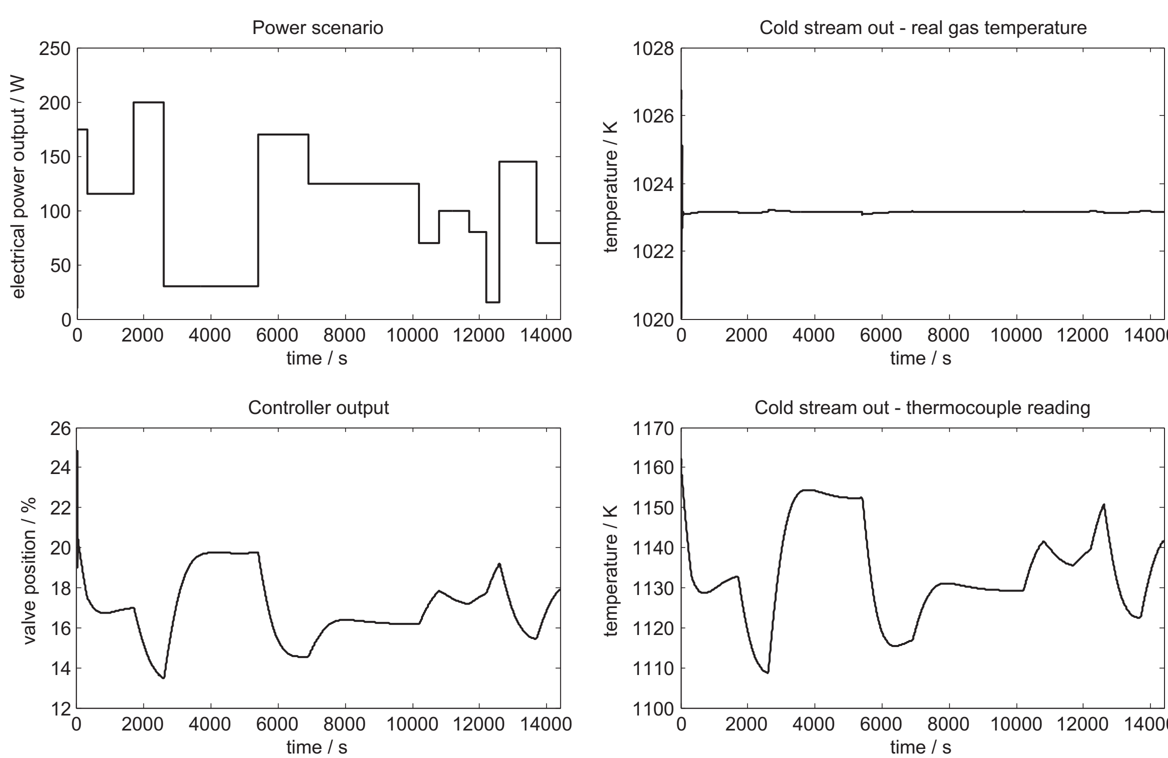

Fig. 3. Power scenario, real gas temperature, thermocouple reading and controller output (valve position) for case 1A of PID control (Table 1). Air ratio is 4 and fuel power input is 1000 W.

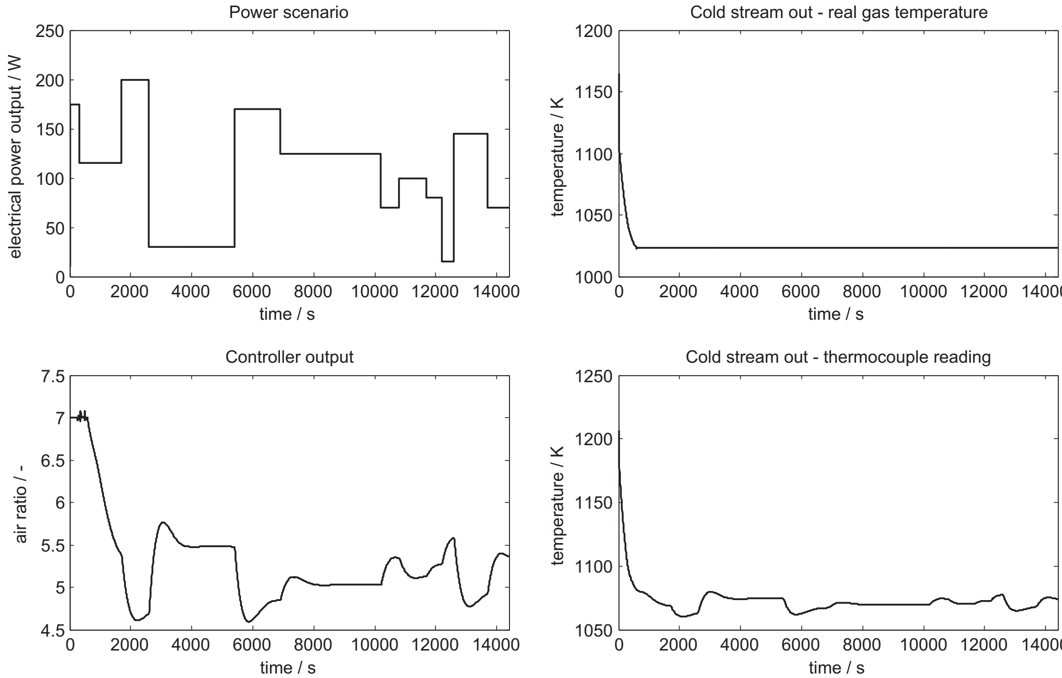

Fig. 4. Power scenario, real gas temperature, thermocouple reading and controller output (air ratio), for case 2A of PID control (Table 1). Valve position is 0 and fuel power input is 1000 W.

(STACK), a counter-flow heat exchanger (HEX), a catalytic partial oxidation reformer (CPOX) where the fuel (natural gas) is reformed and a post combustion component (PB) where the depleted gases from the stack are burnt before entering the hot stream of HEX. The schematic of Fig. 1 depicts also the existence of a bypass circuit, controlled by a valve, with which fresh air is mixed with the air preheated in the heat exchanger before entering the stack.

The heat exchanger and the stack model are 1-dimensional along the gas flow whereas the two reactors (CPOX, PB) are lumped models working in chemical equilibrium. All components in this application are considered adiabatic.

The heat exchanger and the stack models include also models for the thermocouples, i.e. models simulating the operation of thermocouples at locations in the system where they are usually installed to measure the gas temperatures. Like the HEX and STACK models, they are also 1-dimensional and they comprise heat balance equations including radiative and conductive heat exchange with the surrounding solids, convection with the gas, the temperature they are supposed to measure and conduction along the stem [11].

The model was first validated with measurements from the real system [15]. The validation was thermal management-oriented, i.e. the target was to simulate successfully the thermal behaviour of the system as well as the gas streams' pressures. The calibrated parameters were heat transfer and pressure drop coefficients, reaction relaxation factors (factors that deviate the reaction from equilibrium) and other relevant parameters. The electrochemical model was taken from Ref. [6] with some adaptations.

During validation the measured gas temperatures were compared with the simulated thermocouple readings and not with the simulated gas temperatures. This way the bias in the gas temperature measurements was part of the validated mathematical model. More details on the validation process may be sought in Refs. [11,15], while Ref. [15] describes the model in detail.

After validation the calibrated model was used to proceed to experimentations on control, and more specifically to study the effect of the afore-mentioned bias on the system's thermal control. However, it should be noted that for this study certain factors and features of the system are altered compared to the real system for exploratory purposes.

3. Applied control scenarios

Three different single-input–single-output (SISO) PID control schemes were tested on the system. Aim of the control was to obtain and maintain a temperature of 750 °C for the preheated air. The control variables (controller output) were either the position of the bypass valve (see also Fig. 1), or the incoming air ratio (lambda) or the fuel power input. Each PID scheme was tested for two different types of controller input. First the real gas temperature at the exit of the heat exchanger's air stream, as calculated in the simulation was taken into consideration. Second, it was the thermocouple reading at the same point as simulated by the thermocouple model. The following Table 1 summarises the six different cases presented in this article. Each control scenario is coded with a number distinguishing the employed control variable and a letter for the controller input (Fig. 2).

Table 2
PID controller parameters used in the control scenarios.

	Gain K_p	Reset time τ_I	Rate τ_D	Rate limit ω_D
1A	0.896	0.9	1.75	0.05
2A	48	2	5	0.5
3A	2000	20	5	0.5
1B	1.87	1.84	0.5	0.05
2B	48	20	5	0.5
3B	1000	20	5	0.5

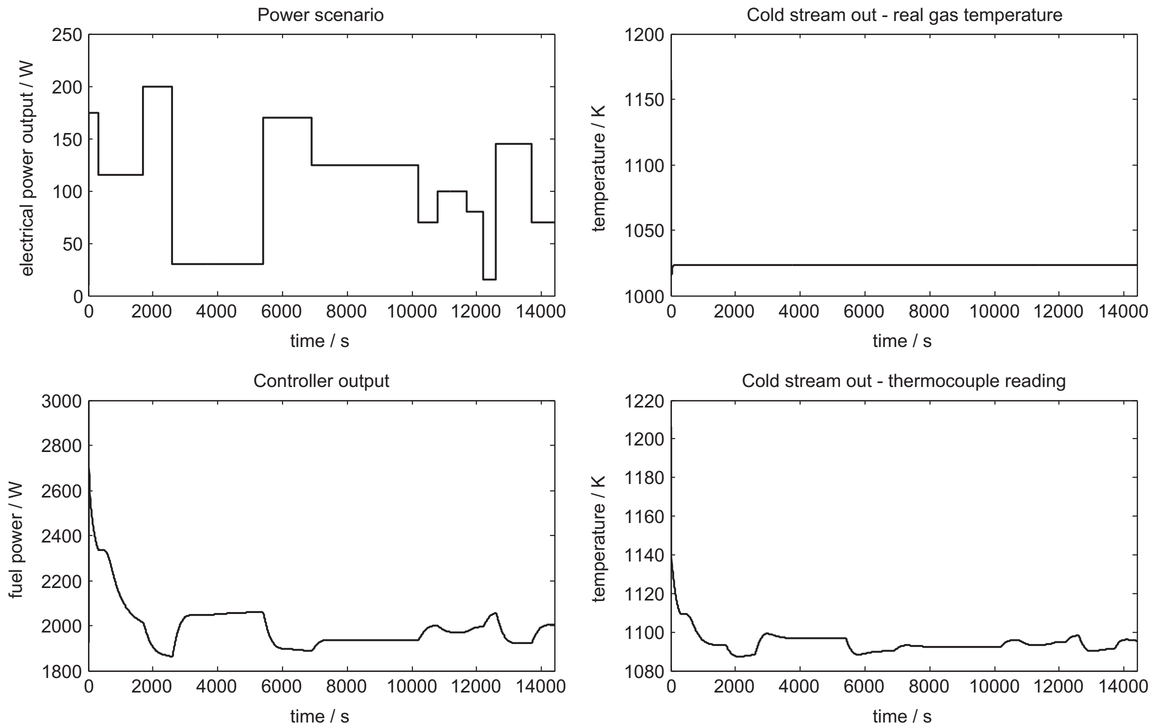

Fig. 5. Power scenario, real gas temperature, thermocouple reading and controller output (fuel power) for case 3A of PID control (Table 1). Valve position is 0 and air ratio 4.

All cases were tested under a 4-h power demand scenario. The scenario is depicted in Fig. 4. It was created with random numbers changing both the power demands and their durations. The power range was between 15 and 200 W.

The controller was integrated in the gPROMS® model using the PID control modules available in the software's library. The controller's transfer function is given in the following Eq. (1) [16]. The derivative term is in filtered form [17].

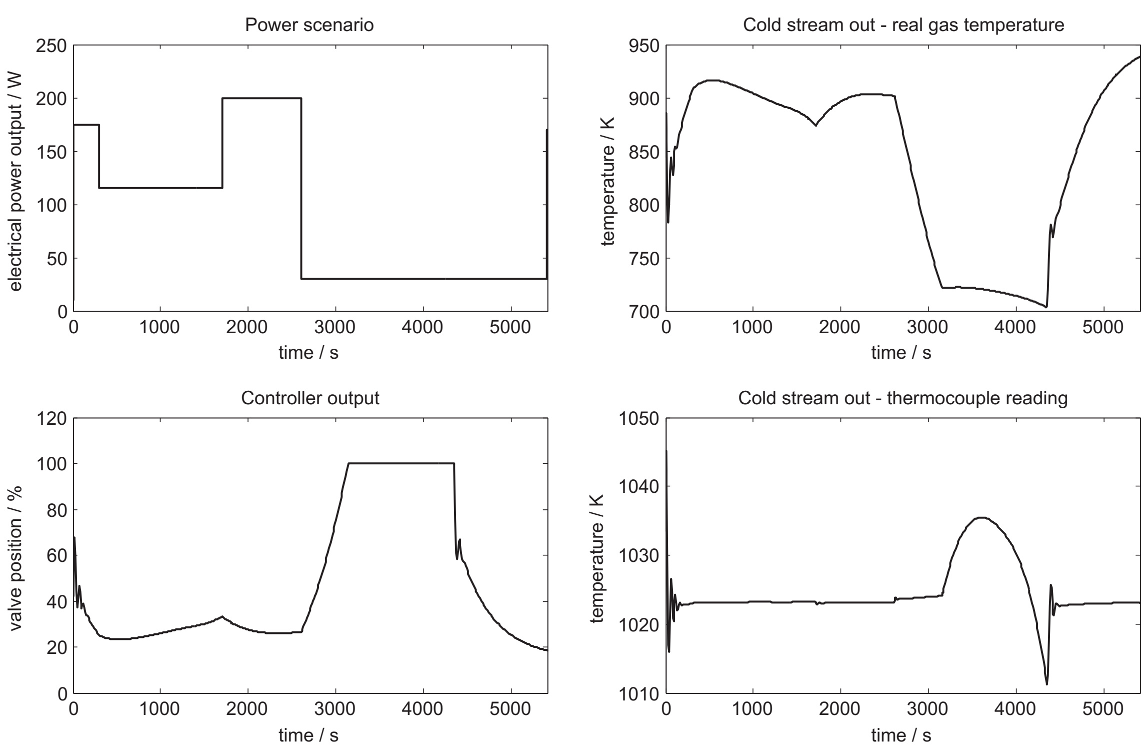

Fig. 6. Power scenario, real gas temperature, thermocouple reading and controller output (valve position) for case 1B of PID control (Table 1). Air ratio is 4 and fuel power input is 1000 W.

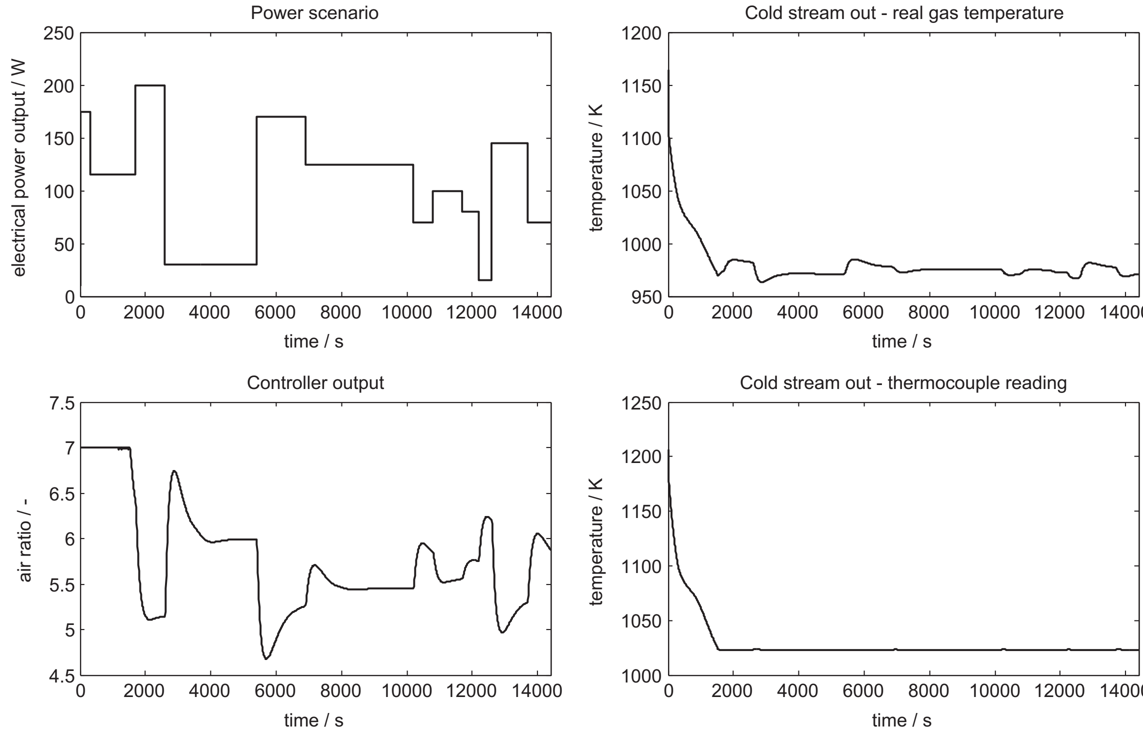

Fig. 7. Power scenario, real gas temperature, thermocouple reading and controller output (air ratio) for case 2B of PID control (Table 1). Valve position is 0 and fuel power input is 1000 W.

$$K_{(s)} = K_p\left(1 + \frac{1}{\tau_I s} + \frac{\tau_D s}{1 + \omega_D s}\right) \quad (1)$$

Its parameters (gain K_p, reset time τ_I of the integral term, rate limit ω_D and rate time of the derivative term τ_D) were calculated using the Ziegler–Nichols method. Despite the high non-linearity of the system, it gave satisfactory results. Only for the case where the control variable was the valve position (1A and 1B), an optimisation algorithm was additionally employed to improve the results. The optimisation was implemented in MATLAB®, using the

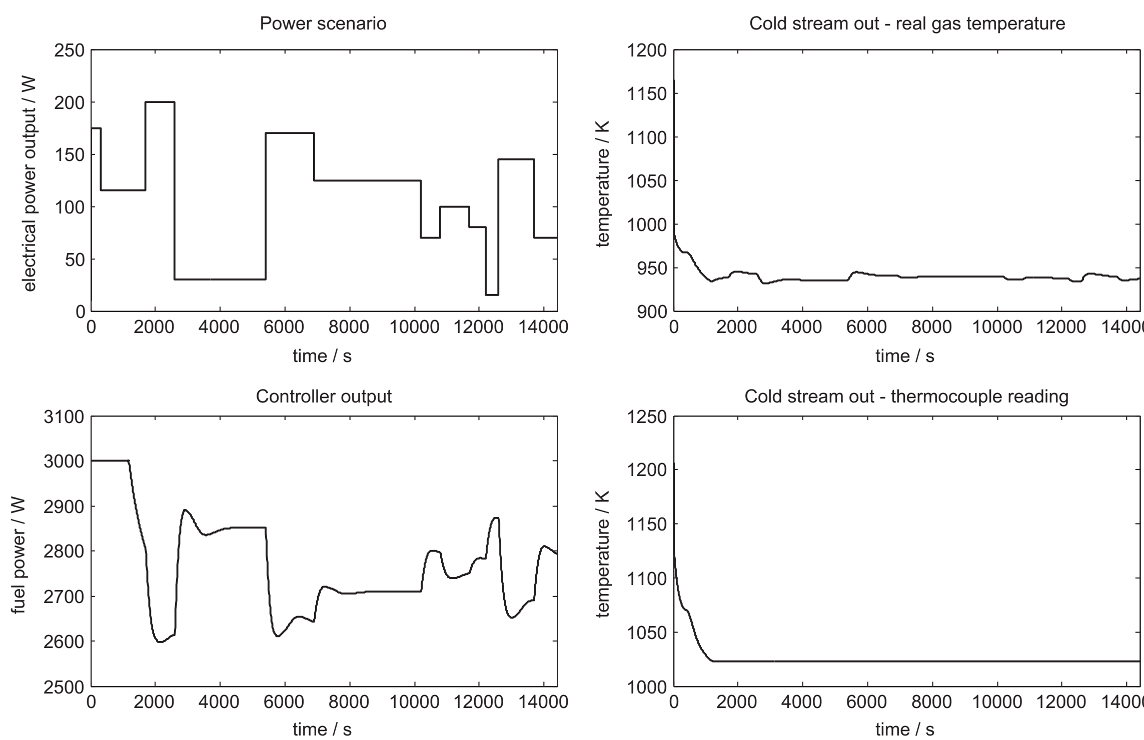

Fig. 8. Power scenario, real gas temperature, thermocouple reading and controller output (fuel input power) for case 3B of PID control (Table 1). Valve position is 0 and air ratio is 4.

Pattern Search algorithm from MATLAB's toolboxes. With lower and upper bounds for the valve opening 0 and 100% respectively (for 100% the system has its highest level of bypass), the algorithm minimised the error between the set and the temperature measurement fed back to the controller. Initially the optimisation took place for the entire duration of the test (14,400 s) but it was observed that restricting to only the first 300 s gave practically the same results, which decreased the calculation strain. For the other control cases (2A/B and 3A/B) the results did not improve substantially with optimisation. Table 2 presents the final values for the parameters.

4. Results and discussion

4.1. Control based on the real gas temperature

Figs. 3–5 depict the response of the system under the three different control outputs for the imposed power demand scenario. On the top left part of each figure the power demand is repeated whereas the right part comprises the temperatures of interest (real gas temperature on top and thermocouple response at the bottom). The bottom left part shows the output of the controller.

The results show that a PID controller may control the preheated air's temperature satisfactorily if it reads the correct gas temperatures. In all three cases the controller maintains successfully the gas temperature at the exit of the heat exchanger to the desired level (750 °C) with an exception for case 2A (control of the air ratio) during the first 600 s of simulation. This was due to the need for excessive mass flow of air to cool the heat exchanger in the beginning of the operation, above the upper limit of 7 that was set for this system. The oscillations observed at the real gas temperature of case 1A are lower than 0.1 °C. Oscillations also exist at the other two cases but they cannot be distinguished because of different scaling.

The simulated thermocouple reading allows an estimation of the measurement error for all three schemes. The error varies from about 80 K to 70 K for cases 2A and 3A respectively up to 110 K for case 1A. Due to the high temperatures on the surrounding solids, the read temperature is always an overestimation of the real temperature. The consequences of this fact are demonstrated in subsection 4.2.

All three controls essentially regulate the flow rate of air in HEX which in turn affects the solid temperature in the area around the thermocouple. As a result the controller output is strongly correlated with the thermocouple indication.

4.2. Control based on the thermocouple reading

4.2.1. Response of the system

The results on the second, more realistic approach are given in Figs. 6–8. It is the case where the gas temperature measurement includes the systematic error due to radiation on the thermocouple. Among the tested control schemes, only cases 2B (Fig. 7) and 3B (Fig. 8) were successful in keeping the system working. Both cases maintained the control input, that is, the thermocouple indication, at the desired levels. The real gas temperature was lower than the target as expected. For 2B the mean value was 974 K oscillating in a range of ±10 K and for 3B the respective value was 938 ± 7 K, i.e. 75–85 K below the set temperature. It is noted that the mean was measured after the initial transient phase of approximately 2000 s until the end of the simulation.

For the same reasons described before, the controller output has a strong correlation with the real gas temperature. This time the correlation is negative and it applies after the transient phase.

Control scenario 1B (Fig. 6) demonstrated the worst impact that biased temperature measurement may have on the operation of the SOFC system. During the first 2600 s of the simulation, the controller maintains a relatively stable temperature for the stack. But when the power demand dropped from 200 W to 30 W, the excessive heat released with the combustion of the introduced fuel increased considerably the temperature of the hot stream in the heat exchanger. The controller responded to this change by opening the valve completely. Although it took 400 s to open the valve, the solid temperature as well as the thermocouple indication kept increasing while the real gas temperature plummeted. It was only when the entire system cooled down, at $t \approx 4350$ s, that the controller responded by closing the bypass. However, it was too late by then. As at $t = 5400$ s there was an increase of power demand from 30 to 170 W the system was too cold to respond and it failed

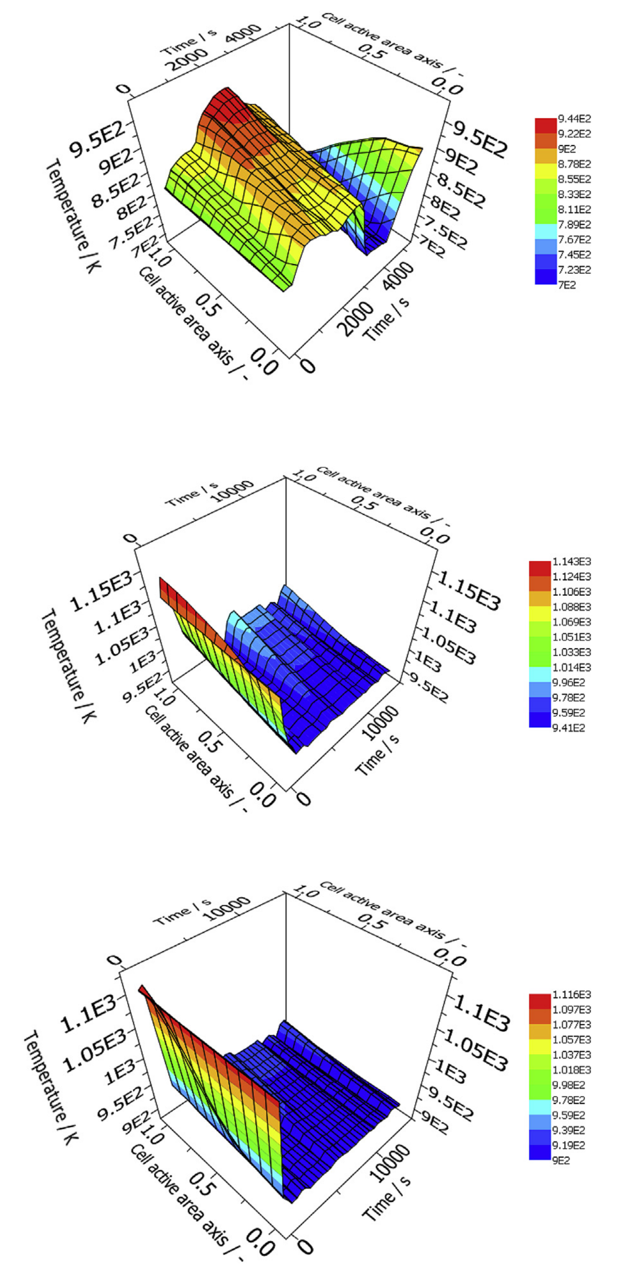

Fig. 9. Evolution of temperature on MEA's active area for 1B (top), 2B (middle) and 3B (bottom) PID control scenarios (colour image in online version).

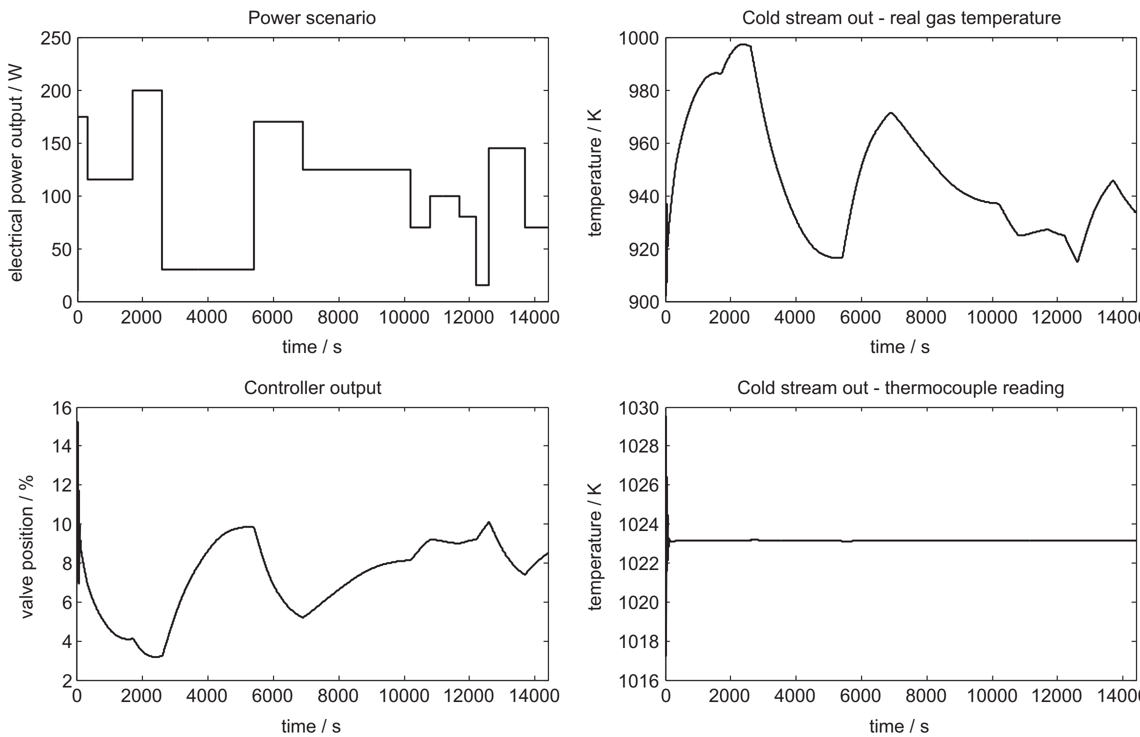

Fig. 10. Power scenario, real gas temperature, thermocouple reading and controller output (valve position) for a variation of case 1B of PID control (Table 1) with increased heat exchanger length.

10 s later. It should be noted that among many optimisation trials the result depicted in Fig. 6 was the one with the longest running time.

4.2.2. *Temperatures on the MEA*

Further to the results presented in the previous three figures, a look at Fig. 9 is also worthwhile. It depicts the temperature evolution along the cell's MEA for all B cases. The two last ones show relatively low temperature gradients, even during the first 600 s of the transient phase. However, the graph for scenario 1B shows very low temperatures after $t = 3000$ s, lower than 750 K, and a very high temperature gradient towards the end of the test. Such operating conditions endanger the operability of the ceramic material.

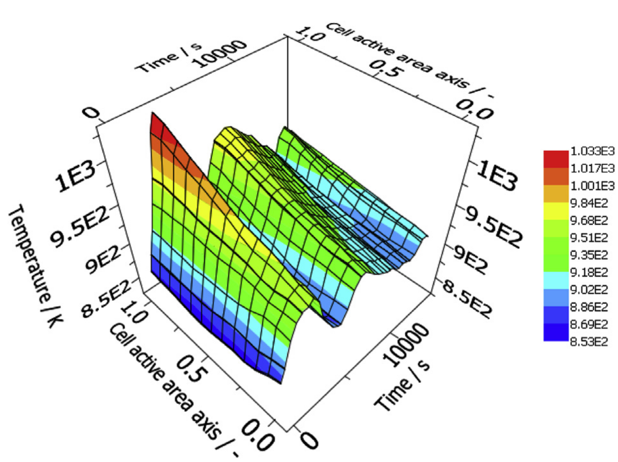

Fig. 11. Evolution of temperature of MEA's active area for case 1B, repeated with increased heat exchanger length (colour image in online version).

4.2.3. *A second attempt on case 1B*

Since the source of the problem is the discrepancy between gas temperature and thermocouple reading, several solutions may be envisaged. One would be to use more complex measurement systems for a better approximation of the real temperature [11]. Another would be to use more advanced control systems, with observers that make estimations on the uncertain temperature [18]. A third solution is to make appropriate design changes on the system that mitigate the discrepancy.

For example an increase of the dimensions of the heat exchanger may provide such mitigation. In order to demonstrate that and to examine whether an SOFC system can indeed function, the case 1B that failed before was reran with increased heat exchanger length. The controller's configuration remained unchanged. The results are depicted in Fig. 10. They show that an increased length allowed the maintenance of the system into operable limits even for an aggressive control variable such as the valve position. Fig. 11 shows however that the temperature gradients on the cells remain important and more advanced control approaches are necessary.

5. Conclusion

Measuring gas temperatures with thermocouples is the typical low-cost approach in fuel cell industry. However, this practice may be the source of serious systematic errors in the control feedback of intermediate or high temperature fuel cells, and they may impede their performance or even jeopardise their operability. In order to analyse the effects of such bias, PID control scenarios were applied on a simulation model of an SOFC system. Two different situations were tested. The first used the real gas temperature as input for the controller. The second used as input the thermocouple reading, where radiation and other phenomena had an effect on the measurement. Three controller outputs were

tested: a) the position of a valve that regulates the quantity of air bypassing the heat exchanger, b) the air ratio (lambda) of the system and c) the quantity of fuel introduced into the system. For the cases where the measurement was unbiased, the controller obtained the desired temperatures for all three controlled variables. On the other hand, when the thermocouple indication was used, the controller had an overestimated input for the gas temperature. With the air excess ratio or the fuel input as controlled variables, the controller was able to keep the air temperature within acceptable limits. When the bypass valve was controlled, the systematic error was so high that the system eventually failed. A simulation of the failed case with longer heat exchanger gave successful results, demonstrating that simple design improvements may improve the situation.

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List of symbols

Latin

HEX	heat exchanger
K_p	gain of the PID controller
$K_{(s)}$	transfer function of the PID controller
MPC	Model Predictive Control
MEA	membrane–electrode assembly
PB	post-combustion component of system
PID	Proportional-Integral-Derivative controller
SISO	single-input–single-output
SOFC	Solid Oxide Fuel Cell
t	time (s)

Greek

λ	air ratio (–)
τ_D	derivative term (rate time) of the PID controller (s)
τ_I	integral term (reset time) of the PID controller (s)
ω_D	rate limit of the derivative term of the PID controller (s^{-1})

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